

Modelling modulus of elasticity of *Pinus pinaster* Ait. in northwestern Spain with standing tree acoustic measurements, tree, stand and site variables

Esther Merlo^{1*}, Juan Gabriel Alvarez-Gonzalez², Oscar Santaclara¹
and Guillermo Riesco²

¹ Madera Plus Calidad Forestal, S.L. Parque Tecnológico de Galicia. Rúa de Vigo, 2.
32900 San Cibrao das Viñas (Ourense), Spain. ² Departamento de Ingeniería Agroforestal.
Unidad de Gestión Forestal Sostenible. Universidad de Santiago de Compostela. Escola Politécnica Superior.
Campus Universitario, s/n. 27002 Lugo, Spain

Abstract

Aim of study: Modelling the structural quality of *Pinus pinaster* Ait. wood on the basis of measurements made on standing trees is essential because of the importance of the species in the Galician forestry and timber industries and the good mechanical properties of its wood. In this study, we investigated how timber stiffness is affected by tree and stand properties, climatic and edaphic characteristics and competition.

Area of study: The study was performed in Galicia, north-western Spain.

Material and methods: Ten pure and even-aged *P. pinaster* stands were selected and tree and stand variables and the stress wave velocity of 410 standing trees were measured. A sub-sample of 73 trees, representing the variability in acoustic velocity, were felled and sawed into structural timber pieces (224) which were subjected to a bending test to determine the modulus of elasticity (MOE).

Main results: Linear models including wood properties explained more than 97%, 73% and 60% of the observed MOE variability at site, tree and board level, respectively, with acoustic velocity and wood density as the main regressors. Other linear models, which did not include wood density, explained more than 88%, 69% and 55% of the observed MOE variability at site, tree and board level, respectively, with acoustic velocity as the main regressor. Moreover, a classification tree for estimating the visual grade according to standard UNE 56544:2011 was developed.

Research highlights: The results have demonstrated the usefulness of acoustic velocity for predicting MOE in standing trees. The use of the fitted equations together with existing dynamic growth models will enable preliminary assessment of timber stiffness in relation to different silvicultural alternatives used with this species.

Key words: stress wave velocity; modulus of elasticity; site index; competition index; stepwise regression; CART.

Introduction

Pinus pinaster Ait. is one of the most important coniferous species used in the timber industry in Spain, especially in Galicia (NW Spain) where it covers around 587,000 ha of land and is the main forest industry resource. More than 2.8 million cubic meters of *Pinus pinaster* round wood are produced annually in Galicia, representing 72% of the total production of the species in Spain. Recent studies have demonstrated the good mechanical properties of Galician *P. pinaster* timber, which make it suitable for structural use (Riesco and Díaz González, 2007; Carballo *et al.*, 2009).

Forest management and climatic and soil factors have important effects on softwood properties (*e.g.* Lasserre *et al.*, 2004; 2008; Moore *et al.*, 2009; 2013; Roth *et al.*, 2007; Watt *et al.*, 2006; 2008). Studies carried out in different regions have assessed the influence of these factors on the variation in wood properties in coniferous species (*e.g.* Lei *et al.*, 2005; Liu *et al.*, 2007, or Ikonen *et al.*, 2008). The use of portable acoustic devices that estimate timber stiffness from measurements made on standing trees (*e.g.* Wang *et al.*, 2001b; 2007; Merlo *et al.*, 2008, 2009; Santaclara *et al.*, 2011) is a key element of these studies. Stiffness (quantified by the modulus of elasticity, MOE) is an important mechanical property of timber and it is commonly measured in machine grading of timber strength. It is also the index parameter considered by

* Corresponding author: maderaplus@maderaplus.es

Received: 05-07-13. Accepted: 28-11-13.

engineers in designing structures for the serviceability limit state under Eurocode 5 (AENOR, 2006). A good relationship between standing tree acoustic measurements and wood properties of the trees would enable the use of acoustic tools to assess the value of timber as structural material. This information would enable the wood processing sector to optimize resources and future investments with the aim of increasing industrial efficiency. The data would enable identification of the proportion of the trees in the stand that could be used for construction. It would also enable identification of those stands of poor structural quality, which could then be managed for other more appropriate purposes.

Determination of the factors that affect stiffness is critical, as this information can be used to develop models that provide predictions about this property across broad environmental gradients. Models that predict MOE on the basis of tree and site variables could be integrated with models describing how silviculture and site characteristics influence this property. This would enable managers to design site-specific silviculture practices to optimise the end-product value.

The aims of this study were to analyze how timber stiffness is influenced by tree, stand and competition characteristics and to propose a model based on acoustic data from standing trees. This would provide a reliable and non-destructive method of predicting the elastic properties of *P. pinaster* wood.

Material and methods

Site description and measurements

The material used in this study was collected from 10 pure mature even-aged *Pinus pinaster* stands located throughout the distribution area of the species in Galicia with ages ranged from 43 to 65 years. With the aim of examining the influence of site factors on wood properties, the stands were subjectively selected to cover the range of site productivity, quantified by site index. Conventional management of maritime pine in Northwestern Spain to yield 300-400 crop trees per hectare at the rotation age was applied to all of the stands.

A rectangular 0.05-ha sample plot (25 × 20 m) was installed in each stand. The following variables were measured for each tree within the plots: X and Y coordinates (m), total height (H, m), diameter at breast height (DBH, cm), average crown width (CW, m) and crown length (CL, m). Stem slenderness and crown ratio were defined as H/DBH and CL/H, respectively.

The stand variables basal area (G), number of stems per hectare (N), mean height (\bar{h}), dominant height (H_0) defined as the mean height of the 100 thickest trees per hectare, and site index at a reference age of 20 years were also calculated for each plot, using the equation proposed by Álvarez González *et al.* (2005). Other tree attributes, such as the presence of forks, broken or defective tops, external resin bleeding, severe lean and other type of malformations, were also recorded.

The stress wave velocity was measured in each stem by using the IML Electronic Hammer (Instrumenta Mechanic Labor GmbH, Germany). The probes were modified to be hammered into trees, allowing penetrating through the bark on the wood. In some cases it was also necessary to remove the bark of the tree before the measure. One measurement was made at each of the four cardinal points on each stem. At each point, measurements were taken until the differences between three consecutive values were less than 100 m/s, and the average value of the three measurements was recorded (Moore *et al.*, 2009). The stress wave velocity of the tree was calculated as the mean value of the four cardinal measurements.

Chemical and physical properties of soil and litter layer were measured in each sample plot. Sub-samples of the mineral soil layer were collected with a steel corer, at 5 points in each sample plot, and were combined to form one bulk sample per plot. These samples were oven-dried at 40°C and sieved at 2 mm for determination of the stoniness. Total C and N in the fine soil fraction were analyzed with a LECO Elemental analyzer. Available P, Ca, Mg, K, Mn, Fe, Cu, Ni, Al and Zn were extracted by the Mehlich 3 procedure (Mehlich, 1984) and were determined by ICP-OES.

At each sampling point, five density cores were collected in a 100 cm³ metal cylinder. The cores were oven-dried at 105°C and weighed to determine the bulk density, following the methodology of Blake and Hartge (1986). The pH was measured in water, with a glass electrode.

To sample the litter layer, 0.3 × 0.3 m square frames were thrown at random within each plot, on 5 occasions. All aboveground soil litter was collected and dried at 40°C to constant weight. The samples were analyzed for pH in water, total C, total N and available macro- and micro-nutrients, using the above-described methods.

Monthly precipitation and mean, maximum and minimum monthly temperatures in each sample plot were obtained from a grid of meteorological stations distributed throughout Galicia, by using the spatial

Table 1. Summary statistics of the site level variation in soil and litter properties and climatic variables

Variable	Mean	Std. Dev.	Maximum	Minimum
<i>Soil properties</i>				
Carbon (%)	7.02	1.78	8.87	4.15
Nitrogen (%)	0.39	0.12	0.56	0.21
pH	4.48	0.43	4.96	3.79
Olsen P (mg/kg)	6.13	1.54	8.28	3.80
Exch. K (mg/kg)	73.93	18.77	96.39	45.84
Exch. Mg (mg/kg)	33.52	12.43	48.69	15.99
Exch. Mn (mg/kg)	27.52	27.49	68.31	1.37
Exch. Ca (mg/kg)	29.39	16.26	54.12	11.14
Exch. Fe (mg/kg)	268.33	84.45	398.06	146.32
Exch. Al (mg/kg)	2,066.02	221.94	2,312.54	1,642.13
Soil organic matter (%)	12.10	3.06	15.28	7.16
<i>Litter chemical properties</i>				
Carbon (%)	44.15	6.41	49.30	31.77
Nitrogen (%)	1.10	0.33	1.65	0.62
Olsen P (mg/g)	0.50	0.12	0.68	0.31
N/P	21.75	4.24	29.59	16.29
Exch. K (mg/g)	0.73	0.42	1.77	0.41
Exch. Mg (mg/g)	1.19	0.41	2.01	0.73
Exch. Mn (mg/g)	0.40	0.42	1.31	0.03
Exch. Ca (mg/g)	2.17	0.62	2.69	1.06
Exch. Fe (mg/g)	3.15	3.69	10.96	0.43
Exch. Al (mg/g)	2.53	2.92	9.68	0.54
<i>Climatic variables</i>				
Mean annual air temperature (°C)	12.57	1.84	14.80	9.46
Mean minimum annual air temperature (°C)	7.66	1.58	9.92	5.17
Mean minimum autumn air temperature (°C)	11.31	2.28	15.31	7.36
Annual rainfall (mm)	1,332.69	474.26	2,350.48	738.00
Summer rainfall (mm)	208.61	59.78	327.61	136.40

interpolation proposed by Rodríguez Guitián (2004). The main soil and litter properties and climatic variables are shown in Table 1.

Lumber processing and wood properties evaluation

A sub-sample of 5-10 well-formed trees per sample plot, of diameter at breast height between 25 and 45 cm, was selected to cover the complete range of stress wave velocities observed in each plot from a total of 410 standing trees evaluated. A total of 73 sample trees were felled and the first 8 meters from the butt were bucked into two logs of 3 and 5 meters. Each log was labelled, the diameter and bark thickness were measured at both ends, and the log position in the tree was recorded. A 10-cm-thick disk was removed at the base of the stem. All the logs were processed in the

same way from debarking to sawing. The logs were debarked and then sawn into structural timber pieces of $200 \times 200 \times 5,000$ mm, $200 \times 150 \times 5,000$ mm, $150 \times 100 \times 3,000$ mm and $150 \times 50 \times 3,000$ mm, depending on log dimensions and log defects. A total of 224 structural pieces were finally obtained (43 of $200 \times 200 \times 5,000$ mm, 38 of $200 \times 150 \times 5,000$ mm, 40 of $150 \times 100 \times 3,000$ mm and 103 of $150 \times 50 \times 3,000$ mm). Each piece was identified by tree number and log position. All pieces were air-dried until the timber reached an equilibrium moisture content of roughly 12%. The modulus of elasticity in bending (MOE) of the timber was determined by the edgewise four-point static bending test, as established by standard UNE-EN 408:2011 (AENOR, 2012). The modulus of elasticity of a specific tree (MOE_{tree}) was calculated as the mean value of the modulus of elasticity of the timber pieces obtained in this tree (MOE_{board}). The modulus of elasticity of each site (MOE_{site}) was calculated as

the weighted mean value of the MOE_{tree} using the number of pieces of each tree as weight.

Each piece was visually graded according to standard UNE 56544:2011 (AENOR, 2011). This standard classifies structural timber on the basis of its defects and dimensions. Grade MEG was applied to structurally-apt material thicker than 70 mm (only pieces of $200 \times 200 \times 5,000$ mm, $200 \times 150 \times 5,000$ mm and $150 \times 100 \times 3,000$ mm were considered) while grades ME-1 or ME-2 were applied to structurally-apt pieces thinner than 70 mm ($150 \times 50 \times 3,000$ mm); pieces not apt for structural use were classified as “excluded”.

For wood density analysis, a rectangular piece of 5×2 mm (a radial segment from pith to bark) was cut from each 10-cm-thick disk. Radial wood samples were dried to equilibrium moisture of 12%, and resins were extracted with a solution of ethanol. A radial X-ray density profile was obtained from each sample by the indirect-reading X-ray densitometry method described by Polge (1966) and adapted by Mothe *et al.* (1998) and Rozenberg (2001). The following parame-

ters were determined in each ring: ring width (mm); earlywood and latewood widths (mm); mean, maximum and minimum wood density (g/cm^3) and earlywood and latewood densities (g/cm^3). The mean wood density (WD) and the latewood width proportion (LWW) were calculated for each radial segment, using the ring variables described. The EW-LW boundary in each growth ring was determined according to the model proposed by Rozenberg (2001). Analysis of the variations in mean wood density from pith to bark of all the sample trees revealed the presence of juvenile wood, at least in the first 10 rings from the pith. This threshold was therefore used to calculate juvenile wood ring width (mm) and juvenile wood density (g/cm^3).

Competition indices

To analyse the effect of competition on wood properties, 7 different competition indices were calculated for each of the 73 sample trees (Table 2). The first

Table 2. Competition indices and corresponding equations tested to analyze the influence of competition on wood properties

Competition index	Equation
Basal area of larger trees (BAL) Wykoff <i>et al.</i> (1982)	$\sum_{j=1}^i \frac{\pi \cdot DBH_j^2}{4} \quad DBH_j \geq DBH_i$
BAL relative	$\frac{BAL_i}{g_{plot}}$
Hegyi (1974)	$\sum_{i \neq j} \frac{DBH_j}{DBH_i \cdot Dist_{ij}}$
Martin and Ek (1984)	$\sum_{i \neq j} \frac{DBH_j}{DBH_i} \cdot \exp \left(\frac{16 \cdot Dist_{ij}}{DBH_i + DBH_j} \right)$
Daniels <i>et al.</i> (1986)	$\frac{DBH_i^2 \cdot n}{\sum DBH_j^2}$
Pukkala and Kolström (1987)	$\sum_{i \neq j} \frac{H_i}{H_j \cdot Dist_{ij}}$
Crown cross-sectional area (CCS)	$\sum_{i \neq j} \frac{CC_j}{CC_i \cdot Dist_{ij}}$

where DBH_i and DBH_j are the diameter at breast height of the sample tree and the competitor tree, respectively (m); g_{plot} is the basal area of the sample plot (m^2); $Dist_{ij}$ is the distance between competitor and sample tree (m); n is the number of competitors; H_i and H_j are the total height of sample and competitor tree, respectively (m) and CC_i and CC_j are the crown cross-sectional-area of sample and competitor tree, respectively, evaluated at 66% of the crown height from the top (m^2) of the sample tree.

two are distance-independent indices, and all trees in each sample plot were considered as possible competitors of the sample tree. The value of the other five competition indices depends on the method used to define neighbouring trees as competitors. In this study, four competitors were considered for each sample tree and each was defined as the nearest tree inside each quadrant delimited by the cardinal points from the sample tree.

The mean, maximum and minimum values and the standard deviation of the main stand and tree variables, the calculated values of the competition indices and wood properties are listed in Table 3.

Table 3. Summary statistics of the main stand and tree variables, including the values of the competition indices used in the study and the main wood properties

Variable	Mean	Std. Dev.	Maximum	Minimum
<i>Stand variables</i>				
Stems per ha	467.71	175.64	726.60	287.98
Basal area (m ² /ha)	51.48	9.88	69.14	37.37
Mean height (m)	21.58	2.05	23.64	18.23
Dominant height (m)	22.89	2.16	25.43	19.59
Site index (m)	12.74	1.61	14.99	9.49
Age (years)	52.00	7.52	65.00	43.00
<i>Tree variables</i>				
DBH (cm)	42.47	5.46	58.45	21.40
Total height (m)	22.88	2.44	27.50	17.30
Stem slenderness	0.55	0.09	0.72	0.35
Crown length (m)	16.10	2.60	20.60	10.60
Crown ratio	0.70	0.07	0.86	0.53
<i>Competition indices</i>				
BAL (m ² /ha)	43.96	23.29	114.54	5.18
BAL relative	0.55	0.22	1.00	0.06
Hegyi (1974)	0.77	0.23	1.54	0.40
Martin and Ek (1984)	43.39	162.80	907.92	4.60
Daniels <i>et al.</i> (1986)	1.23	0.48	2.43	0.57
Pukkala and Kolström (1987)	0.89	0.26	1.72	0.46
Crown cross-sectional area (CCS)	0.78	0.34	2.26	0.30
<i>Wood properties</i>				
MOE (GPa)	11.04	3.77	25.29	4.04
Stress wave velocity (m/s)	2,985.00	3,03.03	4,316.00	2,461.00
Ring width (mm)	3.04	0.79	5.73	1.67
Earlywood width (mm)	2.10	0.54	4.01	1.06
Latewood width (mm)	0.94	0.29	1.72	0.61
Latewood width proportion	0.29	0.05	0.35	0.21
Wood density (g/cm ³)	0.49	0.05	0.61	0.39
Earlywood density (g/cm ³)	0.43	0.04	0.53	0.34
Latewood density (g/cm ³)	0.70	0.06	0.85	0.56
Juvenile wood ring width (mm)	5.14	1.11	7.33	3.55
Juvenile wood density (g/cm ³)	0.49	0.04	0.55	0.45

Modelling methods

A random-effect model was used to estimate the percentage of total variation in MOE_{board} attributable to each stratum (stand, tree and log). A nested structure was assumed for the random effects of tree and site following the model:

$$y_{ijkl} = \mu + S_i + T_{j(i)} + L_{k(ij)} + e_{l(ijk)} \quad [1]$$

where y_{ijkl} is the MOE_{board} on an individual piece of timber, μ is the overall mean, S_i is the random effect of the i th site [$\sim N(0, \sigma_S^2)$], $T_{j(i)}$ is the random effect of the j th tree within the i th site [$\sim N(0, \sigma_T^2)$], $L_{k(ij)}$ is the random effect of the k th log within the j th tree [$\sim N(0, \sigma_L^2)$], and $e_{l(ijk)}$ is the random effect of the l th piece of timber from the k th log [$\sim N(0, \sigma_e^2)$].

Linear models relating the MOE_{site}, MOE_{tree} and MOE_{board} values to the measured tree and stand variables, soil characteristics, climatic variables and other wood properties were developed. Selection of the best set of independent variables was carried out by applying the stepwise variable selection method, combined with preliminary graphical and correlation analyse of the data and an understanding of the fitting process.

To evaluate the presence of multicollinearity among variables in the models analyzed, the variance inflation factors (*VIF*) of all the independent variables was calculated as follows:

$$VIF = \frac{1}{1 - R_i^2} \quad [2]$$

where R_i^2 is the multiple correlation coefficient obtained when the i th independent variable X_i is regressed against all the remaining independent variables in the model. Values up to 10 were accepted, in accordance with Der and Everitt (2002).

Evaluation of the model performance was based on graphical analysis, by plotting the observed against predicted values of the dependent variable, and the studentized residuals against the estimated values residuals and two statistical indices: the root-mean-square error (*RMSE*), which analyzes the precision of the estimates; and the adjusted coefficient of determination (R_{adj}^2), which reflects the part of the total variance that is explained by the model and which takes into account the number of parameters that it is necessary to estimate. These statistics are expressed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - p}} \quad [3]$$

$$R_{adj.}^2 = 1 - \frac{(n-1) \sum_{i=1}^n (y_i - \hat{y}_i)^2}{(n-p) \sum_{i=1}^n (y_i - \bar{y})^2} \quad [4]$$

where y_i , \hat{y}_i , and \bar{y} are the observed, predicted and mean values of the dependent variable, respectively, n the total number of observations, and p the number of parameters in the model.

Finally, a cross-validation approach was used to evaluate the predictive capability of the models. The adjusted model efficiency for the estimates (MEF_{adj}), calculated by equation [4], was estimated by using the residual of each MOE observation, which was obtained by refitting the model without this observation residual. Also, plots of the studentized residuals against the predicted MOE and plots showing the observed against the predicted MOE in cross-validation were analysed to search for systematic trends. All analyses were undertaken in SAS (SAS Institute Inc., 2004).

Visual grading classification

A classification tree was used to relate the visual grades (defined as MEG, ME-1, ME-2 and excluded) to the measured tree and stand variables. Classification tree analysis is a non-parametric technique for the sequential partitioning of a data set composed of a categorical response variable and any number of potential continuous or categorical predictor variables, by use of dichotomous criteria (Breiman *et al.*, 1984). After each split, the technique searches for the predictor variable that provides the most effective binary separation of the range in the response variable. As a result, predictor variables can be used more than once.

The classification tree analysis was performed using the *rpart* package from R (R Development Core Team, 2011; Therneau and Atkinson, 2012). This approach sequentially partitions the data set, on the basis of predictor variables, into the most pure class memberships possible. Instead of applying stopping rules, it generates a sequence of sub-trees by growing a large tree and pruning it back until only the root node is left. Cross-validation is then used to estimate the misclassification cost of each sub-tree by determining the number of correct and incorrect classifications, and the sub-tree with the lowest estimated cost is chosen.

Results

Effect of site and stand variables on mean sample plot MOE_{site}

The Pearson correlation coefficients between the MOE_{site} and climatic and edaphic variables were also calculated. Only four variables were significantly related to MOE_{site} : the soil litter nitrogen (N) fraction ($r = -0.7503$, $p = 0.0199$); the soil litter N/P ratio ($r = -0.8828$, $p = 0.0016$); the mean annual temperature ($r = 0.9231$, $p = 0.0030$) and the mean minimum annual temperature ($r = 0.7212$, $p = 0.0283$).

The MOE_{site} was also strongly correlated with some stand variables. Specifically, the MOE_{site} was significantly and positively related to mean height ($r = 0.6722$, $p = 0.0473$) and site index ($r = 0.6845$, $p = 0.0420$), whereas MOE_{site} was significantly and negatively related to basal area ($r = -0.7005$, $p = 0.0356$). The number of stems per hectare ($p = 0.7381$) and stand age ($p = 0.5668$) were not significantly correlated with MOE_{site} .

Significant and positive correlations were also found between MOE_{site} and mean density ($r = 0.8838$, $p = 0.0016$) and mean stress wave velocity ($r = 0.7586$, $p = 0.0178$).

Effect of site, stand and tree variables on mean tree MOE_{tree} and MOE_{board}

In total, 20 site, tree and stand variables were significantly correlated with MOE_{tree} (Table 4). As expected from the results obtained for the sample plot the mean annual temperature, mean minimum annual temperature, mean height, dominant height and site index were significantly and positively correlated with MOE_{tree} , while the soil litter nitrogen fraction, soil litter N/P ratio, and basal area were significantly and negatively correlated with this parameter. The stand age ($p = 0.2064$) and number of stems per hectare ($p = 0.8382$) were not significantly correlated with MOE_{tree} .

The tree variables most strongly correlated with MOE_{tree} were stem slenderness (positive), and DBH and crown ratio (negative). As regards the competition indices used, only the basal area of largest trees (BAL) and the index proposed by Daniels *et al.* (1986) were significantly (although only just), linearly correlated with MOE_{tree} , indicating a reduction in this parameter when tree competition increases.

Table 4. Site, tree and stand variables that were significantly correlated with MOE. The Pearson's correlation coefficient and the significance level are shown for each variable

Variable	Sampled trees	Correlation coefficient (<i>r</i>)	Prob > <i>r</i> under $H_0: r=0$
<i>Site variables</i>			
Litter N%	73	-0.6037	<0.0001
Litter N/P	73	-0.6679	<0.0001
Mean annual temperature (°C)	73	0.7212	<0.0001
Mean minimum annual temp. (°C)	73	0.4589	<0.0001
<i>Stand variables</i>			
Basal area (m ² /ha)	73	-0.6637	<0.0001
Mean height (m)	73	0.5949	<0.0001
Dominant height (m)	73	0.5220	<0.0001
Site index (m)	73	0.5721	<0.0001
<i>Tree variables</i>			
DBH (cm)	73	-0.4489	<0.0001
Total height (m)	73	0.4996	<0.0001
Stem slenderness	73	0.6060	<0.0001
Crown ratio	73	-0.4173	0.0002
<i>Competition indices</i>			
BAL	73	-0.3326	0.0040
Daniels <i>et al.</i> (1986)	73	-0.2462	0.0358
<i>Wood properties</i>			
Stress wave velocity (m/s)	73	0.6408	<0.0001
Latewood width proportion	73	0.6319	<0.0001
Wood density (g/cm ³)	73	0.7340	<0.0001
Earlywood density (g/cm ³)	73	0.4839	<0.0001
Latewood density (g/cm ³)	73	0.5673	<0.0001
Juvenile wood density (g/cm ³)	73	0.5961	<0.0001

As expected, the mean density was the wood property most closely correlated with MOE_{tree} ($r = 0.7340$, $p < 0.0001$), although strong and positive relationships between MOE_{tree} and latewood width proportion ($r = 0.6319$, $p < 0.0001$) and all of the within-ring density parameters based on the earlywood-latewood boundary were also found.

The significant and positive correlation between stress wave velocity and MOE_{tree} confirmed the previously reported potential of acoustic technology as a good estimator of the mechanical properties of wood in standing trees (e.g. Wang *et al.*, 2001b; Carter *et al.*, 2005; Ishiguri *et al.*, 2008).

Regarding the values of the modulus of elasticity at board level (MOE_{board}), the same 20 site, stand and tree variables showed significant correlations.

Models to estimate modulus of elasticity MOE_{site}, MOE_{tree} and MOE_{board}

The results of the random-effects model indicated that of the overall variation in MOE_{board}, the 52.65% was attributed to differences between sites, the 28.01% to differences between trees within a site, the 5.63% to differences between logs within a tree and the 13.71% to differences between pieces within a log.

Two different linear models to estimate MOE_{site}, MOE_{tree} and MOE_{board} from site, tree and stand characteristics were fitted. Firstly, linear models including all the variables previously showed to be significantly correlated with MOE_{site}, MOE_{tree} and MOE_{board} were fitted. The stepwise variable selection method, together with an understanding of the process modelled, was used to select the best set of independent variables. The values of the variance inflation factor (VIF) were analysed to prevent multicollinearity. To analyse the effect of log position on MOE_{boards}, a dummy variable with a value of 1 for the 1st log and 0 for the 2nd log was included as an independent variable. The parameter estimates and the goodness of fit statistics of models 1, 3 and 5 for MOE_{site}, MOE_{tree} and MOE_{board}, respectively are shown in Table 5.

All the parameters were significant at the 0.05 probability level; the values of VIF did not indicate any problem of collinearity, and the values and signs of the parameters were biologically consistent. At site level, modulus of elasticity was related to stress wave velocity, wood density and site index (model 1). This model explained almost the 98% of the total variability observed. MOE_{tree} was best predicted by wood density, stress wave velocity, dominant height and soil litter N/P ratio (model 3). This model explained 73.73% of the total variance in modulus of elasticity with a value of the adjusted model efficiency of the estimates (MEF_{adj}) of 68.01%. At board level, the best set of independent variables included wood density, stress wave velocity, total height, dominant height and soil litter N/P ratio (model 5), explaining the 60.33% of the total variability in MOE_{board}. The parameter associated with the log position was not significant at the 5% level and therefore, model 5 was refitted without this variable. Plots of studentized residuals of the three models provided random patterns around zero, with homogeneous variance and no detectable significant trends.

As the objective of the study was to obtain models for estimating MOE that are easy to use from a prac-

Table 5. Summary of model statistics and coefficient values for the multiple linear regression model of MOE including structural wood variables

Equation form and parameter estimates	R^2_{adj}	RMSE	MEF _{adj}
<i>Stand-level equations (n = 10)</i>			
(Model 1) $MOE_{site} = -21.9739 + 0.0023SWV + 36.8856WD + 0.6723SI$	0.9791	2.0876	0.9338
(Model 2) $MOE_{site} = -21.1544 + 0.0075SWV + 0.7820SI$	0.8853	4.5458	0.7801
<i>Tree-level equations (n = 73)</i>			
(Model 3) $MOE_{tree} = -13.5834 + 0.0038SWV + 17.04105WD + 0.4067H_0 - 0.1856N/P$	0.7373	3.0507	0.6801
(Model 4) $MOE_{tree} = 0.0047SWV - 6.0740BAL - 0.1056G + 0.5097SI - 0.0776DBH$	0.6921	3.1634	0.6195
<i>Board-level equations (n = 224)</i>			
(Model 5) $MOE_{board} = -14.1119 + 0.0035SWV + 18.5879WD + 0.1992H - 0.1777N/P + 0.2268H_0$	0.6033	2.3719	0.5709
(Model 6) $MOE_{board} = 0.0045SWV - 0.57942BAL - 0.0865G + 0.3746H_0 - 0.1259DBH$	0.5512	2.5229	0.5142

N/P: soil litter Nitrogenous-Phosphorus ratio. SI: site index, defined as the dominant height (m) at a reference age of 20 years. SWV: stress wave velocity (m/s). WD: wood density (g/cm³). H₀: dominant height (m). BAL is the basal area of largest trees (m²/ha). G: stand basal area (m²/ha). DBH: diameter at breast height (cm). H: total height of the tree (m).

tical point of view, in a second step, linear models without including independent variables difficult to measure (wood properties and soil and climatic variables) were fitted. The dummy variable for log position was included in model 6. The results of models 2, 4 and 6 for MOE_{site}, MOE_{tree} and MOE_{board}, respectively are shown in Table 5.

All of the parameters were again found to be significant at the 5% significance level, except for the intercept in models 4 and 6. Therefore, these models were refitted without an intercept. The new models showed biologically consistent values and signs, and the VIF values did not indicate any problems of multicollinearity. At site level, modulus of elasticity was best predicted by stress wave velocity (SWV) and site index (SI). Model 2 explained the 88.53% of the observed variability. The best set of independent variables for MOE_{tree} (model 4) included stress wave velocity, DBH, basal area of larger trees (BAL), stand basal area (G) and site index (SI). At board level, the parameter associated with the log position was not significant and, therefore, model 6 was refitted without this variable. Finally, the best set of independent variables for model 6 included the same variables that MOE_{tree} (model 4) and the total height of the tree. All the independent variables included in model 4 and 6 are easy to measure in a forest inventory. The scatter plots of observed modulus of elasticity values (GPa) against predicted modulus of elasticity obtained with models 3 and 4 at tree level and 5 and 6 at board level are shown in Fig. 1.

Visual grading

The application of standard UNE 56544:2011 (AENOR, 2011) to visual grading resulted in a 83.47% of the pieces thicker than 70 mm (121 pieces) being classified as structurally-apt materials ("MEG"), while 27.91% of pieces thinner than 70 mm (103 pieces) were classified as structurally-apt materials of the top grade ("ME-1") and 48.84% of these pieces were assigned to the second grade ("ME-2"). The classification tree obtained is shown in Fig. 2.

Discussion

Effect of site and stand variables on mean sample plot MOE_{site}

The strong negative correlation between the soil litter N/P ratio and MOE_{site} may be due to the influence of phosphorus (P) assimilation on frost tolerance. A high concentration of P in the soil litter (low N/P ratio) may increase frost tolerance, so that a higher proportion of latewood and consequently a higher MOE_{site} (due to the greater stiffness of latewood than of earlywood) would be obtained. The observed relationship between latewood width proportion and soil litter N/P ratio ($r = -0.6781$, $p < 0.0001$) supports this hypothesis. In a study with young *Pinus radiata* stands, Watt *et al.* (2006) also observed significant correlations between organic phosphorus and MOE, although

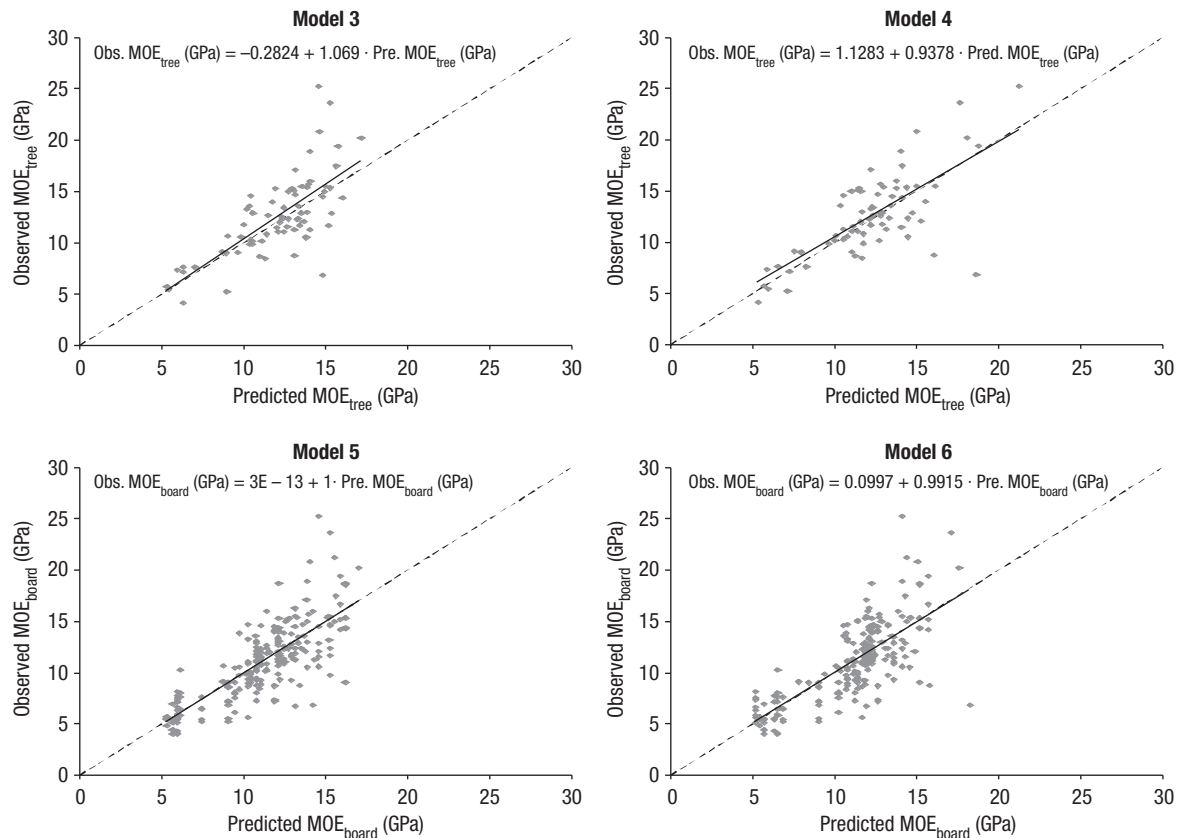


Figure 1. Plots of observed versus predicted values of MOE at tree (upper row) and board (lower row) level obtained from the models including wood density and site variables as independent variables (left) and from the models that do not include these variables (right). The solid line represents the linear model fitted to the scatter plot of data, and the dashed line is the 1:1 line.

the results indicated that MOE was relatively insensitive to P fertilization (with considerable increments, in the order of two- to three-fold).

The significant and positive linear relationship between MOE_{site} and mean annual temperature and mean minimum annual temperature may be due to the effect

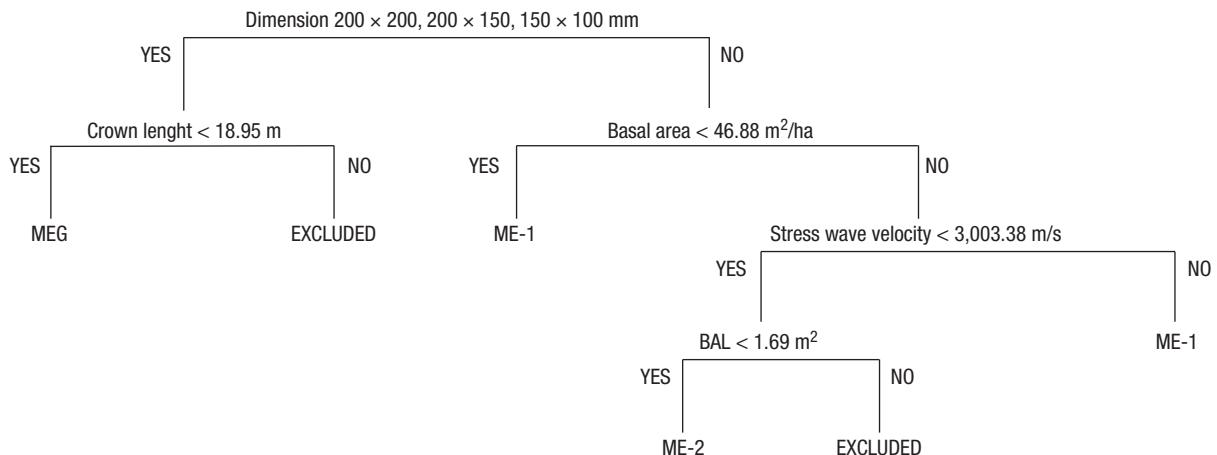


Figure 2. Classification tree for estimating the visual grade according to standard UNE 56544:2011 (AENOR, 2011) for *Pinus pinaster* timber in Galicia. The rpart package from R (R Development Core Team, 2011; Therneau and Atkinson, 2012) was used to obtain the classification tree.

of temperature on latewood development. As latewood fibres are stiffer than earlywood, higher temperatures (especially in autumn) could yield a higher percentage of latewood, and therefore a higher overall MOE of the timber. Similar results have been reported for young *Pinus radiata* stands (Watt *et al.*, 2006; Watt *et al.*, 2008).

The MOE_{site} was also strongly correlated with site index. Watt *et al.* (2006) reported that site had a significant effect on MOE in young *Pinus radiata* stands; however, Liu *et al.* (2007) did not observe a significant correlation between site index and MOE in *Picea mariana* stands, although these authors considered that this was due to the lack of variability in site quality. The significant negative correlation observed between basal area and MOE_{site} is consistent with findings for other tree species, such as *Pseudotsuga menziesii* (Walford, 1985), *Picea abies* (Kliger *et al.*, 1995), *Pinus resinosa* (Deresse *et al.*, 2003), *Pinus radiata* (Lasserre *et al.*, 2004) or *Picea sitchensis* (Moore *et al.*, 2009).

Neither the number of stems per hectare nor stand age ($p = 0.5668$) were significantly correlated with MOE_{site}. Similar results were reported by Moore *et al.* (2009) for *Picea sitchensis* stands in the United Kingdom, where evidence of correlations between these variables and MOE was inconclusive, although stand age and number of stems per hectare were finally included as independent variables in a linear model proposed by these authors to estimate MOE. Gains in MOE attributable to increased number of stems have been found in different studies (e.g. Biblis *et al.*, 1995; Wang and Ko, 1998; Chuang and Wang, 2001; Wang *et al.*, 2001a; Zhang *et al.*, 2002; Lasserre *et al.*, 2004; 2008; Waghorn *et al.*, 2007a, b). However, in the present study, this variable did not have a significant effect, probably because the range of stand densities (175-726 stems/ha) was not large enough. Nevertheless, the above mentioned correlations should be confirmed with further research including a database with a broader range of ages and number of stems per hectare to identify the key variables affecting the MOE_{site}.

Effect of site, tree and stand variables on mean tree MOE_{tree} and MOE_{board}

The strong and positive correlation observed between MOE and stem slenderness has a sound theoretical basis. Based on Euler's buckling formula, the cri-

tical height ($h_{critical}$) that a tree stem can reach before it undergoes elastic buckling depends on MOE, green wood density (ρ_{green}) and stem diameter (DBH), as in the following expression (Greenhill, 1881):

$$h_{critical} = K \left(\frac{MOE}{\rho_{green}} \right)^{1/3} DBH^{2/3} \quad [5]$$

where K is a constant. Under competition, light demanding species, such as maritime pine, give priority to height growth at the expense of diameter increment, which increases the stem slenderness. When tree heights are relatively close to the critical buckling height, alterations in wood properties may successfully prevent Euler buckling by increasing the density-specific stiffness (MOE/ρ_{green}); this is mainly accomplished through increments in MOE, as green density is relatively constant (Lasserre *et al.*, 2005; Watt *et al.*, 2006). Similar results were found for other coniferous species such as *Cupressus lusitanica* (Watt *et al.*, 2008), *Picea mariana* (Lei *et al.*, 2005; Liu *et al.*, 2007) and *Pinus taeda* (Roth *et al.*, 2007).

Previous studies have also reported a strong negative relationship between DBH and MOE, e.g. in *Picea abies* (Haartveit and Flate, 2002), four softwood species (Wang *et al.*, 2002), *Picea mariana* (Liu *et al.*, 2007) and *Picea sitchensis* (Moore *et al.*, 2009). This can be explained by assuming that trees with higher DBH have wider rings and, consequently, lower percentage of latewood and, as latewood fibres are stiffer than earlywood, the lower percentage of latewood in larger trees could account for the low MOE observed in these trees. Such a negative linear correlation implies that selection of a tree by diameter alone could negatively affect the mechanical properties of wood. However, selection based on the slenderness ratio or a combination between diameter and acoustic velocity appears to be associated with better mechanical properties (Merlo *et al.*, 2008).

The negative and significant correlation observed between crown ratio and MOE at tree and board level was also reported for other coniferous species such as *Picea mariana* (Liu *et al.*, 2007) and *Picea sitchensis* (Moore *et al.*, 2013).

As regards the observed effect of competition on MOE, our results are consistent with previous reports of a significant negative relationship between rate of diameter growth and stiffness (Walford, 1985; Kliger *et al.*, 1995; Deresse *et al.*, 2003, or Lasserre *et al.*, 2004). In a study of the effect of silvicultural mana-

gement on wood properties in *Pinus sylvestris* and *Picea abies*, Ikonen *et al.* (2008) observed a similar effect of competition on wood properties. These authors fitted ring-based models to estimate wood density along the stems for both species, and both models predicted slightly lower wood density for dominant trees in thinned and unthinned stands and, as a consequence, lower MOE.

The strong and positive relationship between MOE at tree and board level and latewood width proportion ($r=0.6319$, $p<0.0001$) was probably due to the importance of this proportion in wood density. Studies assessing genetic and phenotypic effects on wood characteristics in *Pinus pinaster* have indicated that earlywood characteristics are prone to genetic control, whereas latewood components are more strongly influenced by environmental factors (Gaspar *et al.*, 2008a,b). These studies have also indicated the high heritability of wood density and the high genetic correlation between wood density and early wood density (Gaspar *et al.*, 2008a), suggesting that breeding programmes to select this wood property by increasing either earlywood density, latewood percent, or both of these traits, would be profitable.

The observed positive correlations between the within-ring density parameters, based on the earlywood-latewood boundary, and MOE have been also previously reported, *e.g.* for *Picea sitchensis* (Gentner, 1985), for *Larix kaempferi* (Takata and Hirakawa, 1996) and for *Pseudotsuga menziesii* (Rozenberg *et al.*, 1999).

Visual grading

Crown length was the main predictor variable in the classification tree obtained. This parameter classified the pieces in MEG or “excluded” categories for materials thicker than 70 mm. Values of crown length higher than 18.95 m led to the pieces being categorized as “excluded”, independently of other tree or stand variables. Basal area was the main predictor variable for materials thinner than 70 mm. Tree materials from stands with a basal area smaller than 46.88 m²/ha were categorized as ME-1 pieces. Stress wave velocity and basal area of larger trees were also significant predictors for classifying the sample pieces for materials thinner than 70 mm. Considering all sample pieces, 70.09% of the pieces were correctly classified, with 95.05, 76.94 and 25.00% of correct classifications for “MEG”, “ME1” and “ME2” categories, respectively.

The percentage of “ME-2” category correctly classified was very low, although 64% of these pieces were classified as “excluded”. The most critical error of the proposed tree would be classification of excluded material in some of the structurally-apt material categories (“MEG”, “ME1” and “ME2”); only 4.46% of the pieces were wrongly classified in this way. This type of wrong classification constitutes a loss in safety in the structural use of the products obtained from the graded stems. Therefore, from a conservative point of view, high safety factors should be applied in further calculations. On the other hand, the probability of excluding a structurally-apt piece (14.29%) should be minimized as it represents an underestimation of the quality of the material and a wrong reduction in the timber valuation.

Since the classification obtained in this study is based on a limited number of sample plots, the approach should be considered preliminary. Nonetheless, the method appears to be suitable as a first step in forest management decision-making regarding the most appropriate silvicultural schedule for obtaining structural timber in *Pinus pinaster* stands.

Conclusions

Structural static bending modulus of elasticity (MOE) is an important indicator of timber quality. In this study, the influence on MOE of site characteristics, competition and tree and stand variables was analyzed, and a stepwise regression method was used to identify the best variables, including acoustic velocity and wood characteristics, for estimating MOE at three different levels: site, tree and board. The results indicate that acoustic technology is effective for evaluating the structural quality of standing trees. The inclusion of acoustic velocity in this type of models would improve quantification of the effects of forest management and silvicultural treatments on wood quality and selection of the best material for tree breeding programmes. Prior classification of industrial supplies, based on the acoustic velocity of standing trees, would improve utilization of the timber and thus provide significant financial advantages to the industry.

More than 52% of the total variation in modulus of elasticity was attributed to between-stand differences and the mean annual temperature and the soil litter N/P ratio were the site variables more directly related to MOE. The influence of environmental factors was al-

so pointed by the inclusion of site index in the models being excluded the edaphic and climatic variables. However, as the results are based on data from 10 pure and even-aged stands, further studies on the influence of this kind of variables on the wood properties should be carried out by analysing additional samples.

Nevertheless, the above-mentioned restriction does not reduce the value and applicability of the models developed for predicting MOE. In addition, the simple classification system presented enables preliminary assessment of the visual grade for structural timber of any *Pinus pinaster* standing tree by using common tree and stand variables and acoustic velocity, while minimizing overestimation of quality in the structural grade assignment process.

Acknowledgements

This work was mainly carried out within the Galician regional project PIDGT (07MRU004CT) and the national project MICINN PSE.310000-2008 co-financed with FEDER funds from the European Union. The financial support is gratefully acknowledged. We also thank Miguel Romero and Fernando Gómez who collaborated in field and laboratory work, as well as all staff at the Exfopino sawmill who helped in the sawing process.

References

- AENOR, 2006. Eurocode 5: Design of timber structures – Part 1-1: General-Common rules and rules for buildings. AENOR, Madrid, Spain.
- AENOR, 2011. UNE 56544:2011. Visual grading for structural sawn timber. Coniferous timber. AENOR, Madrid, Spain.
- AENOR, 2012. UNE-EN 408:2011. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. AENOR, Madrid, Spain.
- Álvarez González JG, Ruiz González AD, Rodríguez Soalleiro RJ, Barrio Anta M, 2005. Ecoregional site index models for *Pinus pinaster* in Galicia (northwestern Spain). *Ann For Sci* 62: 115-127.
- Biblis EJ, Carino H, Brinker R, McKee CW, 1995. Effect of stand density on flexural properties of lumber from two 35-year-old Loblolly pine plantations. *Wood Fiber Sci* 27: 25-33.
- Blake GR, Hartge KH, 1986. Bulk Density. In: *Methods of soil analysis, Part I. Physical and mineralogical methods*, 2nd ed (Klute A, ed). Agronomy Monograph n° 9. pp: 363-375.
- Breiman L, Friedman JH, Olshen RA, Stone CJ, 1984. Classification and regression trees. Chapman & Hall, New York, USA. 359 pp.
- Carballo J, Hermoso E, Fernández-Golfín JI, 2009. Mechanical properties of structural maritime pine sawn timber from Galicia (*Pinus pinaster* Ait. ssp. *atlantica*). *Invest Agrar Sist Recur For* 18, 152-158.
- Carter P, Briggs D, Ross RJ, Wang X, 2005. Acoustic testing to enhance western forest values and meet customer wood quality needs. USDA Forest Service General Technical Reports PNW 642, 121-129.
- Chuang ST, Wang SY, 2001. Evaluation of standing tree quality of Japanese cedar grown with different spacing using stress-wave and ultrasonic-wave methods. *J Wood Sci* 47, 245-253.
- Daniels RF, Burkhardt HE, Clason TR, 1986. A comparison of competition measures for predicting growth of loblolly pine trees. *Can J For Res* 16: 1230-1237.
- Der G, Everitt BS, 2002. A handbook of statistical analysis using SAS, 2nd ed. Chapman & Hall, CRC. 392 pp.
- Deresse T, Shepard RK, Shaler SM, 2003. Microfibril angle variation in red pine (*Pinus resinosa* Ait.) and its relation to the strength and stiffness of early juvenile wood. *Forest Prod J* 53: 34-40.
- Gaspar MJ, Louzada JL, Aguiar A, Almeida MH, 2008a. Genetic correlations between wood quality traits of *Pinus pinaster* Ait. *Ann For Sci* 65: 703.
- Gaspar MJ, Louzada JL, Silva ME, Aguiar A, Almeida MH, 2008b. Age trends in genetic parameters of wood density components in 46 half-sibling families of *Pinus pinaster* Ait. *Can J For Res* 38: 1470-1477.
- Gentner R, 1985. Appréciation non destructive de la qualité du bois d'arbres sur pied: cas de l'épicéa de Sitka [*Picea sitchensis* (Bong.) Carr.], rapport ERQB Inra Nancy, ENITEF, France. 98 pp.
- Greenhill AG, 1881. Determination of the greatest height consistent with stability that a vertical pole or mast can be made, and of the greatest height to which a tree of given proportions can grow. *Proc Camb Philos Soc* 4: 65-73.
- Haartveit EY, Flate PO, 2002. Mechanical properties of Norway spruce lumber from monocultures and mixed stand – modeling bending stiffness and strength using stand and tree characteristics. In: *connection between silviculture and wood quality: modeling approach and simulation software*, IUFROWP S5.01-04Workshop (Springs HH, ed). British Columbia, Canada, September.
- Hegyí F, 1974. A simulation model for managing jackpine stands. In: *Growth models for tree and stand simulation*. Proc IUFRO meeting S4.01.04 (Fries J, ed). Royal College of Forestry, Stockholm, Sweden. pp: 74-90.
- Ikonen VP, Peltola H, Wilhelmsson L, Kilpeläinen A, Väisänen H, Nuutinen T, Kellomäki S, 2008. Modelling the distribution of wood properties along the stems of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) as affected by silvicultural management. *For Ecol Manage* 256: 1356-1371.

- Ishiguri F, Matsui R, Iizuka K, Yokota S, Yoshizawa N, 2008. Prediction of the mechanical properties of lumber by stress-wave velocity and Pilodyn penetration of 36-year-old Japanese larch trees. *Holz Roh Werkst* 66: 275-280.
- Kliger IR, Perstorper M, Johansson G, Pellicane PJ, 1995. Quality of products from Norway spruce. Part 3. Influence of spatial position and growth characteristics on bending stiffness and strength. *Wood Sci Technol* 29: 397-410.
- Lasserre JP, Mason E, Watt M, 2004. The influence of initial stocking on corewood stiffness in a clonal experiment of 11-year-old *Pinus radiata* D. Don. *New Zeal J For* 49: 18-23.
- Lasserre JP, Mason E, Watt M, 2005. The effects of genotype and spacing on *Pinus radiata* (D. Don) corewood stiffness in a 11 year old experiment. *For Ecol Manage* 205: 375-383.
- Lasserre JP, Mason E, Watt M, 2008. Influence of the main and interactive effects of site, stand stocking and clone on *Pinus radiata* D. Don corewood modulus of elasticity. *For Ecol Manage* 255: 3455-3459.
- Lei YC, Zhang SY, Jiang Z, 2005. Models for predicting lumber bending MOR and MOE based on tree and stand characteristics in black spruce. *Wood Sci Technol* 39: 37-47.
- Liu C, Zhang SY, Cloutier A, Rycabel T, 2007. Modeling lumber bending stiffness in natural black spruce stands using stand and tree characteristics. *For Ecol Manage* 242: 648-655.
- Martin GL, Ek AR, 1984. A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth. *For Sci* 30: 731-743.
- Mehlich A, 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Comm Soil Sci Plant An* 15: 1409-1416.
- Merlo E, Zas R, Piñeiro G, Pedras F, 2008. Variabilidad de parámetros de calidad de madera entre y dentro de procedencias de *Pseudotsuga menziesii*. *Cuadernos de la Sociedad Española de Ciencias Forestales* 24: 262-266.
- Merlo E, Santaclara O, Pedras XF, 2009. Relationship between stress-wave velocity of standing tree and wood quality in 27 year old Douglas-fir. In: 16th International non-destructive testing and evaluation of wood symposium, WOOD NDT, Beijing, China, December.
- Moore JR, Lyon AJ, Searles GJ, Vihermaa LE, 2009. The effects of site and stand factors on the tree and wood quality of Sitka spruce growing in the United Kingdom. *Silva Fenn* 43: 383-396.
- Moore JR, Lyon AJ, Searles GJ, Lehneke SA, Ridley-Ellis DJ, 2013. Within-and between-stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery. *Ann Sci For* 70: 403-415.
- Mothe F, Duchanois G, Zannier B, Leban JM. 1998. Microdensitometric analysis of wood samples: data computation method used at INRA-ERQB (CERD programme). *Ann Sci For* 55: 301-313.
- Polge H, 1966. Établissement des courbes de variation de la densité du bois par exploration densitométrique de radiographies d'échantillons prélevés à la tarière sur des arbres vivants. Application dans les domaines technologiques et physiologiques. Doctoral thesis. Université de Nancy, France.
- Pukkala T, Kolström T, 1987. Competition indices and the prediction of radial growth in Scots pine. *Silva Fenn* 21: 55-67.
- R Development Core Team, 2011. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>
- Riesco G, Díaz González J, 2007. Características físicas de la madera de pino procedente de raleos en el noroeste de España. *Maderas. Ciencia y Tecnología* 9: 233-244.
- Rodríguez Guitián MA, 2004. Aplicación de criterios botánicos para a proposta de modelos de xestión sustentable das masas arborizadas autóctonas do Subsector Galaico-Asturiano Septentrional. Doctoral thesis. University of Santiago de Compostela, Spain.
- Roth BE, Li X, Huber DA, Peter GF, 2007. Effects of management intensity, genetics and planting density on wood stiffness in a plantation of juvenile loblolly pine in the southeastern USA. *For Ecol Manage* 246: 155-162.
- Rozenberg P, 2001 Contribution à l'étude de la variabilité génétique des propriétés du bois chez *Picea abies* (L.) Karst et *Pseudotsuga menziesii* (Mirb.) Franco. Doctoral thesis. ENGREF, INRA, Orléans, France.
- Rozenberg P, Franc A, Mamdy C, Launay J, Schermann N, Bastien JC, 1999. Genetic control of stiffness of standing Douglas fir; from the standing stem to the standardised wood sample, relationships between modulus of elasticity and wood density parameters. Part II. *Ann For Sci* 56: 145-154.
- Santaclara O, Álvarez JG, Merlo E, 2011. Modeling structural lumber quality for *Pinus pinaster* Ait. in northwestern Spain using standing tree acoustic assessment, stand variables and tree characteristics. In: 17th International non-destructive testing and evaluation of wood symposium, WOOD NDT. Sopron, Hungary, September. pp: 127-134.
- SAS Institute Inc, 2004. SAS/STAT[®] 9.1 User's Guide. Cary, NC: SAS Institute Inc, 283 pp.
- Takata K, Hirakawa Y, 1996. Variation in growth ring parameters among Japanese larch from different provenances. In: Recent advances in wood anatomy (Donaldson LA, Singh A, Butterfield BG, Whitehouse LJ, eds). Proceedings of the Third Pacific Regional Wood Anatomy Conference, Rotorua. pp: 351-356.
- Therneau TM, Atkinson B, 2012. Package rpart. Version 3.1-52. <http://cran.r-project.org/web/packages/rpart/index.html> Accessed 27 May 2013.
- Walford GB, 1985. The mechanical properties of New Zealand-growth radiata pine for export to Australia. *FRI Bulletin* 93. Forest Research Institute, New Zealand Forest Service. 27 pp.
- Waghorn MJ, Watt MS, Mason EG, 2007a. Influence of tree morphology, genetics, and initial stand density on outerwood modulus of elasticity of 17- year-old *Pinus radiata*. *Forest Ecol Manage* 244: 86-92.
- Waghorn MJ, Mason EG, Watt MS, 2007b. Influence of initial stand density and genotype on longitudinal varia-

- tion in modulus of elasticity for 17-year-old *Pinus radiata*. *Forest Ecol Manage* 252: 67-72.
- Wang SY, Ko CY, 1998. Dynamic modulus of elasticity and bending properties of large beams of Taiwan-grown Japanese cedar from different plantation spacing sites. *J Wood Sci* 44: 62-68.
- Wang X, Ross RJ, Mattson JA, Erickson JR, Forsman JW, Geske EA, Wehr MA, 2001a. Several nondestructive evaluation techniques for assessing stiffness and MOE of small-diameter logs. Res Pap FPL-RP-600. U. Department of agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA. 12 pp.
- Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD, 2001b. Nondestructive evaluation of standing trees with a stress wave method. *Wood Fiber Sci* 33: 522-533
- Wang X, Ross RJ, Brashaw BK, Erickson JR, Forsman JW, Pellerin R, 2002. Diameter effect on stress-wave evaluation of modulus of elasticity of logs. In: *Proceedings of the 13th International Symposium on Non-destructive Testing of Wood* (Beall FC, ed). Forest Products Society, Madison, WI, USA. pp: 149-156.
- Wang X, Ross RJ, Carter P, 2007. Acoustic evaluation of wood quality in standing trees. Part I. Acoustic wave behavior. *Wood and Fiber Sci* 39(1): 28-38.
- Watt MS, Moore JR, Façon JP, Downes GM, Clinton PW, Coker G, Davis MR, Simcock R, Parfitt RL, Dando J, Mason EG, Bown HE, 2006. Modelling the influence of stand structural, edaphic and climatic influences on juvenile *Pinus radiata* dynamic modulus of elasticity. *For Ecol Manage* 229: 136-144.
- Watt MS, Clinton PW, Coker G, Davis MR, Simcock R, Parfitt RL, Dando J, 2008. Modelling the influence of environment and stand characteristics on basic density and modulus of elasticity for young *Pinus radiata* and *Cupressus lusitanica*. *For Ecol Manage* 255: 1023-1033.
- Wykoff WR, Crookston NL, Stage AR, 1982. User's guide to the stand prognosis model. *Int For and range Exp Sta Gen Tech Rep INT-133*.
- Zhang SY, Chauret G, Ren HQ, Desjardins R, 2002. Impact of initial spacing on plantation black spruce lumber grade yield, bending properties, and MSR yield. *Wood Fiber Sci* 34: 460-475.